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SHORT-TIME STRESS RUPTURE OF PRESTRESSED TITANIUM ALLOYS UNDER RAPID HEATING CONDITIONS

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16. Abstract

This paper discusses short-time creep-rupture life properties of four preloaded titanium alloys under rapid heating conditions. The specimens were resistantly heated, and some comparisons were made with radiantly heated specimens.

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INTRODUCTION

Specific time-temperature-strength data for evaluation of launch vehicle materials that are to be subjected to a particular set of flight conditions are necessary because during launch a rapid heating rate is coupled with a prestressed system and the standard available creep and stress rupture information is usually not sufficient. As pointed out in References 1 and 2, extrapolation cannot be employed because time-dependent phenomena such as stress relief, recrystallization, aging, and overaging may significantly affect the strength of materials in high-temperature service. The investigations in References 3, 4, 5, and 6 were all directed toward a specific need, just as this investigation was directed toward providing specific data on four titanium alloys.

MATERIAL AND METHODS

The four titanium alloys selected for this investigation are described in Table 1. Figure 1 shows the microstructure of the four alloys. Alloys 52 and 64 have long been popular, and they are the most widely used alloys of the titanium family. Alloy 52 has a single alpha phase microstructure, and alloy 64 has a duplex alpha-beta microstructure. Alloy 64 was tested in both the annealed and heat-treated conditions, and both structures are shown. Alloy 64 is widely used in space-vehicle tankage and pressure vessels. Alloys 555 and 6242 are non-heat-treatable alpha alloys that were developed especially for elevated temperature service. Alloy 6242 is of recent development, whereas alloy 555 is an older alloy that has had limited use. The microstructure of alloy 555 is single phase; however, it was difficult to show the grain boundaries without producing etch pits. The microstructure of alloy 6242 appears to be two phase, even though it is classified as an alpha alloy. The 2% molybdenum stabilizes the beta phase and produces a duplex "alpha-lean beta" structure. The manufacturer, therefore, classifies it as a "super" alpha alloy.*

Table 1—Alloy identification.

Alloy number	Nominal chemical composition (percent by weight)						Alloy type	GSFC analysis (percent by weight)					
	Ti	Al	Sn	Zr	Mo	V		Ti	Al	Sn	Zr	Mo	V
52	Bal.	5	2.5				Alpha	Bal.	5.50	2.78			
555	Bal.	5	5	5			Alpha	Bal.	4.63	4.45	5.32		
6242	Bal.	6	2	4	2		Alpha	Bal.	5.96	1.92	4.17	2.16	
64	Bal.	6				4	Alpha-beta	Bal.	6.04				4.14

Note: One sheet of (0.08-in.-thick) material was used for each alloy.

The test method consisted of three phases: (1) prestressing by means of either hydraulic or deadweight loading; (2) heating to the test temperature 1000°, 1200°, 1400°, or 1600°F; and (3) recording the stress-rupture life. A programed (straight line) heating time of 10 seconds was used. The resistantly heated specimens followed the program and reached the test temperature in 10 seconds. The radiantly heated specimens took 20 seconds to reach test temperature. In all cases, the temperature deviations were from +6 to 0 F° over a 1-1/2-in. length.

Figure 2a shows the setup for resistant heating, and Figure 2b shows the setup for radiant heating. The same equipment, such as holders and cooling blocks, were used with both heating methods. Both methods were used in conjunction with hydraulic loading, whereas only resistant heating was employed with deadweight loading. The temperature for all tests and the hydraulic loading were programed and controlled using the Model TM6-MB Universal Testing Machine. The deadweight loading employed a 20 000-lb Satec unit.

*A future paper will cover the metallography and fractography of these alloys in greater detail.

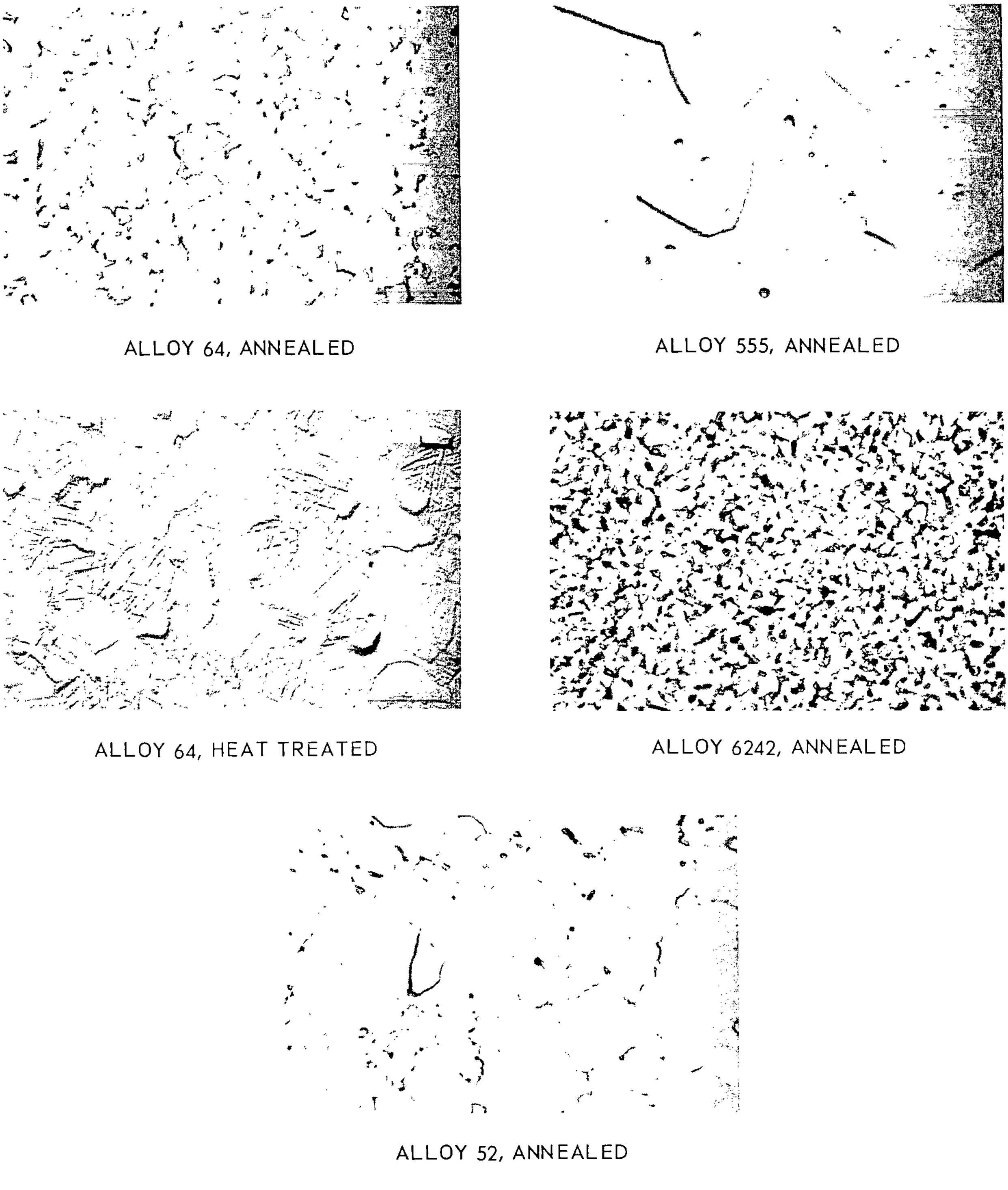
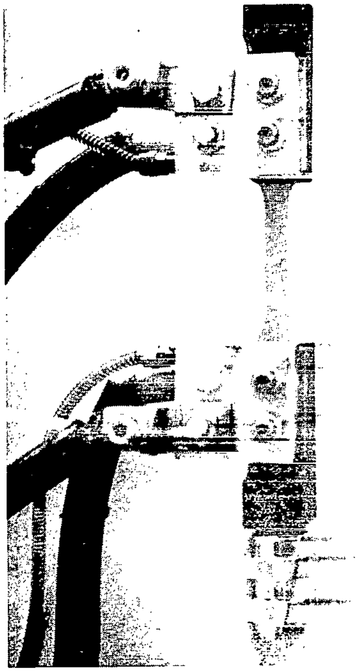
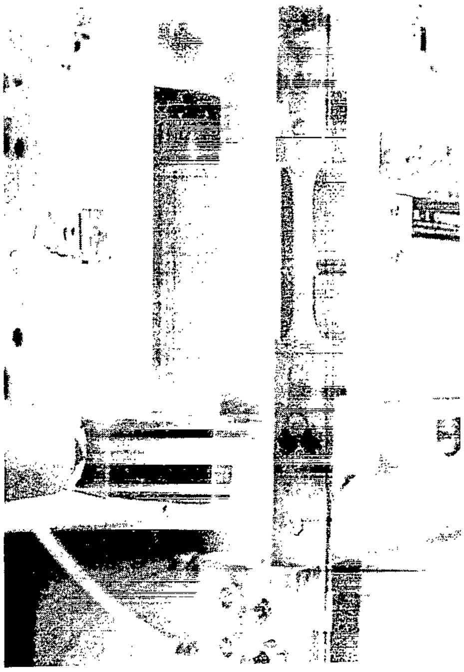


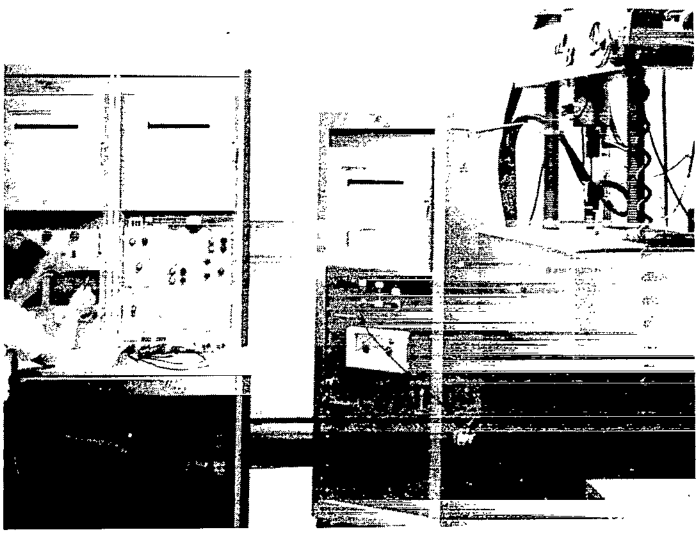
Figure 1—Microstructure of the titanium alloys, Kroll's etchant (750 ×).



RESISTANT HEATING (0.25 ×)



OPEN RADIANT HEATER (0.25 ×)



CONTROLLERS, PROGRAMERS, AND HYDRAULIC LOAD FRAME

Figure 2—The equipment used.

TEST RESULTS AND DISCUSSION

The literature recognizes that various heating methods can be employed; however, most investigators assume that information obtained using various heating methods are interchangeable. In this investigation, resistant heating was the main method used; however, resistant and radiant heating are compared for one alloy. Some observations are noted about the difference in stress-rupture life of alloy 64 in the annealed versus heat-treated conditions. Tensile data (Table 2) were determined for each temperature and for room temperature.

The results of the investigation are graphically presented in plots of fracture time versus prestress (Figures 3 through 6). (In all cases, the reported fracture times are the times at temperature.) Tables A1 through A4 contain the plotted data of Figures 3 through 6 and are included for reference in Appendix A.

Tests on alloy 555 were conducted on specimens taken from both the longitudinal and transverse directions. Specimens of this alloy were both resistantly and radiantly heated. Figure 3 shows that neither the method of heating nor the direction from which the specimens were taken affected the stress-rupture life at the plotted test temperatures. The data for the other alloys were obtained from resistantly heated longitudinal specimens.

At temperatures of 1200°, 1400°, and 1600° F, a transition range (represented by the knee of the plotted curves of Figures 3 through 6) is present for all alloys. Except for heat-treated alloy 64, the plotted curves (Figures 3 through 6) for all alloys at the 1000° F temperature are narrow with respect to the prestress range and approach a straight line. At 1000° F, alloys 555 and 6242 (Figures 3 and 4) were particularly prone to the tendency described above and exhibited very narrow prestress ranges. Some metallurgical straining-recovery phenomena could explain the narrow prestress range and spread in test life at 1000° F for all alloys. Two 1000° F curves (Figure 6) are plotted for alloy 64. One curve represents the alloy in the annealed condition, and the other curve is for the alloy in the heat-treated condition. The standard heat treatment given the alloy is presented in Table 2. The heat-treated alloy was capable of sustaining greater stress levels for comparable periods of time at 1000° F than was the annealed alloy. However, the beneficial effects of the heat treatment were quickly eliminated at the higher temperatures of 1200° and 1400° F, as depicted in Figure 6. These heat-treatment effects are also reflected in the values listed for the ultimate tensile strengths given in Table 2.

A preload stress equivalent to the ultimate tensile strength can be supported for only very short times by all alloys at any of the test temperatures. For instance, the tensile strength of alloy 52 (Table 2) was 24 600 psi at 1400° F. When loaded to a prestress of 25 000 psi, the stress-rupture life at 1400° F was 44 to 60 s. Similar comparisons can be made for all alloys.

Table 2—Mechanical properties.

Alloy	Room temp. hardness (Rc)	Ultimate tensile strength (psi)					Room temp. yield strength (0.2% offset) (psi)	Percent elongation (2 in.)				
		Room temp.	1000° F	1200° F	1400° F	1600° F		Room temp.	1000° F	1200° F	1400° F	1600° F
555	31	126 300	78 000	69 300	44 300	22 700	118 400	17	21	14	18	19
6242	35	150 500	103 500	77 700	35 300	12 100	146 600	12	10	10	21	27
52	35	142 100	80 800	59 200	24 600	12 400	136 000	15	11	15	30	45
64	35	142 500	79 200	52 300	28 100	12 500	138 700	12	11	16	24	32
HT 64*	37	160 000	99 000	54 900	27 000	12 500	152 500	3	8	12	20	30

*Solution heat treated at 1700° F, (30 min at temperature); quenched in water; and aged 5 hr at 950° F.

Notes: 1. Each value represents the average of at least three tests.

2. The strength values listed are within ±500 psi. The room temperature elongation values are within ±0.5%.

3. The elevated temperatures were held within +6 to 0 F° of the listed values.

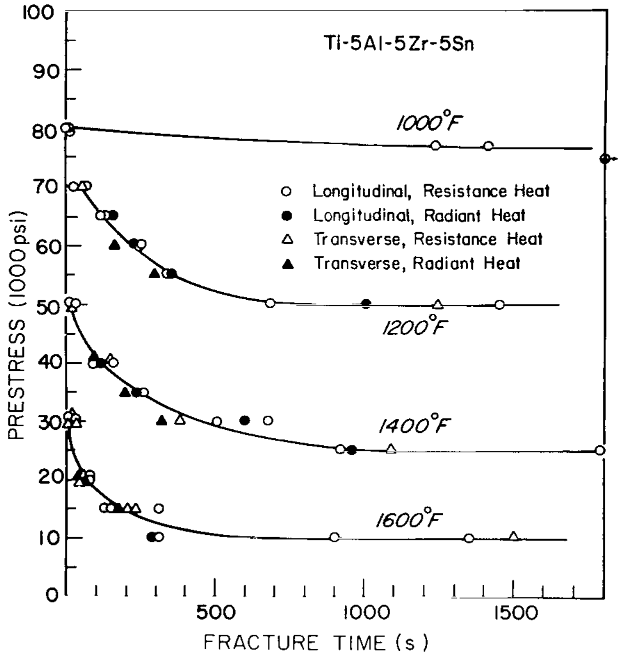


Figure 3—Stress-rupture curves for alloy 555.

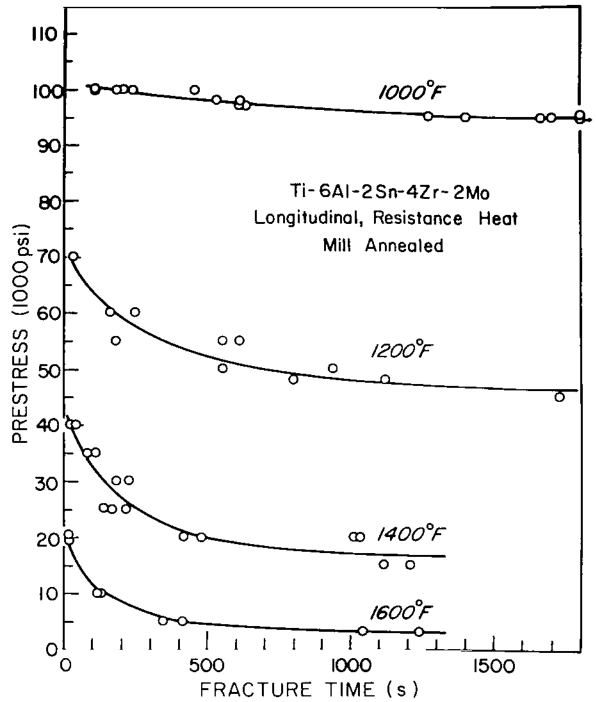


Figure 4—Stress-rupture curves for alloy 6242.

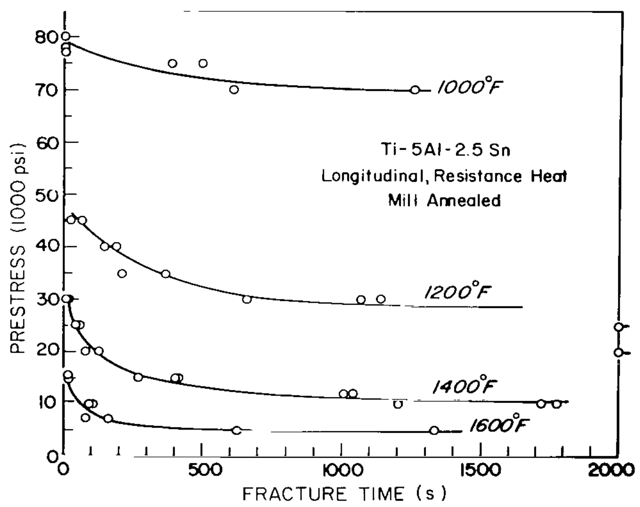


Figure 5—Stress-rupture curves for alloy 52.

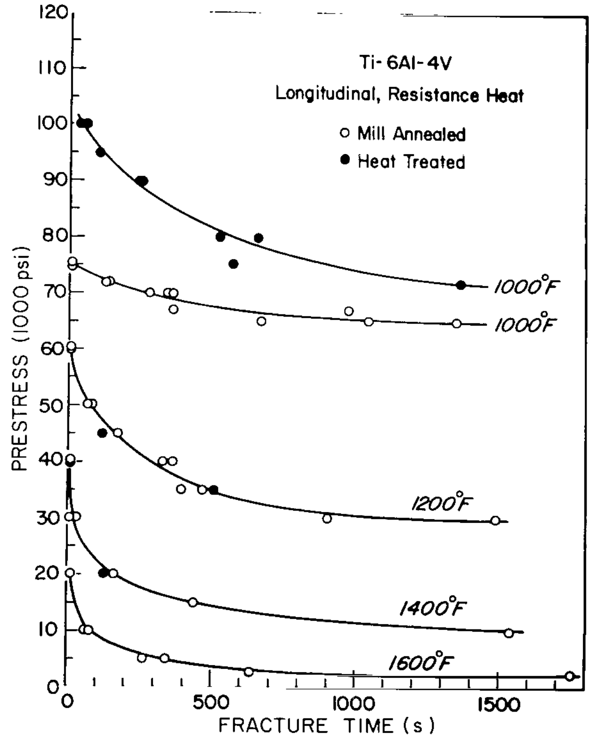


Figure 6—Stress-rupture curves for alloy 64.

The mechanical properties (Table 2) were used primarily as a guide in conducting the stress-rupture tests. Alloy 555 (developed for elevated temperature service) had the lowest ultimate tensile strength of any of the alloys at room temperature and at 1000°F. Compared to alloy 555, the other alloy developed for elevated temperature service (6242) was found to have superior tensile strengths through 1200°F. At temperatures of 1400° and 1600°F, the tensile strengths of alloy 555 were higher than the tensile strengths of the other alloys. At 1600°F, the tensile strength of alloy 6242 was lower than the ultimate strength of any alloy tested.

Some indication of the ductility as measured by percent of elongation can be obtained from the data in Table 2. However, as pointed out in Reference 7 and substantiated by this study, resistance heating causes questionable elongation values after specimen necking occurs. The data presented in Table 3 for alloy 555 show that radiantly heated specimens elongate 3 to 7 percent more than resistantly heated specimens at comparable test temperatures. Because of a rate effect, the resistantly heated tensile specimens had lower elongation values than did the resistantly heated rupture test specimens. Thus, if one wishes to measure ductility, some method other than resistant heating should be used to determine it.

Table 3—Elongation comparisons.

Temp. (°F)	Percent elongation obtained from all rupture tests		Percent elongation from tensile tests
	Resistant	Radiant	Resistant heat
Room temp.			17
1000	23	-	21
1200	17	20	14
1400	25	31	18
1600	30	37	19

Note: These values represent an average of all tests run at the particular temperature.

SUMMARY

The stress-rupture life exhibited by titanium alloy 555 is independent of the method of heating and the orientation of the specimen. From this, it was assumed that the other titanium alloys would react in a like manner.

At the test temperature of 1000°F, the strengthening effects (as measured by stress-rupture life and tensile properties) of heat-treated alloy 64 are pronounced, but they are quickly eliminated at test temperatures of 1200°F and above.

A comparison of two alloys (Figures 3 and 4 and Table 2) developed for elevated temperature service shows that at temperatures of 1400° and 1600°F, alloy 555 is superior to alloy 6242 with regard to tensile and stress-rupture properties. The tensile properties of alloy 6242 are superior at test temperatures of 1200° and 1000°F; however, the stress-rupture curves (Figures 3 and 4) are nearly identical at 1200°F.

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Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt Maryland, May 11, 1970
492-02-04-01-51

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APPENDIX A—DATA FOR FIGURES 3 THROUGH 6

Table A1—Data for Figure 4 (Ti-6Al-2Sn-4Zr-2Mo).

Test temp. (°F)	Prestress (psi)	Test life (s)	Test temp. (°F)	Prestress (psi)	Test life (s)
1200	70 000	33	1600	20 000	15
"	60 000	245	"	"	14
"	"	154	"	10 000	130
"	55 000	180	"	"	122
"	"	550	"	5000	342
"	"	610	"	"	409
"	50 000	550	"	3000	1241
"	"	935	"	"	1042
"	48 000	800			
"	"	1120			
"	45 000	1730	1000	100 000	454
			"	"	240
1400	40 000	44	"	"	203
"	"	20	"	"	180
"	35 000	109	"	"	240
"	"	83	"	"	104
"	30 000	225	"	"	104
"	"	181	"	98 000	531
"	25 000	169	"	"	606
"	"	136	"	97 000	622
"	"	214	"	"	597
"	20 000	486	"	95 000	1275
"	"	412	"	"	1848
"	"	1010	"	"	1800
"	"	1035	"	"	1405
"	15 000	1115	"	"	1713
"	"	1202	"	"	1667

Notes: 1. All specimens were taken longitudinal to the rolling direction.

2. All specimens were resistance heated.

3. The temperatures were held within +6 to 0 F° of the listed values over a 1.5-in. length.

Table A2—Data for Figure 5 (Ti-5Al-2.5Sn).

Test temp. (°F)	Prestress (psi)	Test life (s)	Test temp. (°F)	Prestress (psi)	Test life (s)
1000	80 000	1	1400	25 000	44
"	78 000	2	"	"	60
"	77 000	2	"	20 000	73
"	75 000	498	"	"	125
"	"	389	"	15 000	266
"	70 000	1260	"	"	410
"	"	608	"	"	407
			"	12 000	1005
1200	45 000	70	"	"	1035
"	"	28	"	10 000	1202
"	40 000	190	"	"	1720
"	"	146	"	"	1775
"	35 000	370			
"	"	208	1600	15 000	15
"	30 000	660	"	"	17
"	"	1140	"	10 000	43
"	"	1070	"	"	54
"	25 000	3630	"	7000	155
"	20 000	4500+	"	"	74
1400	30 000	12	"	5000	1331
"	"	28	"	"	627

Notes: 1. All specimens were taken longitudinal to the rolling direction.

2. All specimens were resistance heated.

3. The temperatures were held within +6 to 0 F° of the listed values over a 1.5-in. length.

Table A3—Data for Figure 6 (Ti-6Al-4V).

Test temp. (°F)	Prestress (psi)	Test life (s)	Condition*
1000	100 000	58	HT
"	"	31	HT
"	95 000	102	HT
"	90 000	245	HT
"	"	255	HT
"	80 000	520	HT
"	"	650	HT
"	75 000	567	HT
"	72 000	1361	HT
1000	75 000	3	Ann
"	"	7	"
"	72 000	127	"
"	"	132	"
"	70 000	338	"
"	"	275	"
"	"	358	"
"	67 000	968	"
"	"	355	"
"	65 000	1345	"
"	"	1035	"
"	"	662	"
1200	60 000	7	Ann
"	"	6	"
"	50 000	82	"
"	"	62	"
"	45 000	170	"
"	"	113	HT
"	40 000	360	Ann
"	"	325	"
"	35 000	390	"
"	"	468	"
"	"	508	HT
"	30 000	1488	Ann
"	"	902	"

Table A3 (concluded)

Test temp. (°F)	Prestress (psi)	Test life (s)	Condition*
1400	40 000	9	Ann
"	"	3	HT
"	30 000	5	Ann
"	"	33	"
"	20 000	154	"
"	"	126	HT
"	15 000	438	Ann
"	10 000	1534	"
1600	20 000	11	Ann
"	10 000	76	"
"	"	63	"
"	5000	261	"
"	"	340	"
"	2700	636	"
"	2500	1342	"
"	2500	1775	"

*HT—Heat treated in accordance with standard practices.

Ann—Mill annealed.

Notes: 1. All specimens were taken longitudinal to the rolling direction.

2. All specimens were resistance heated.

3. The temperatures were held within +6 to 0 F° of the listed values over a 1.5-in. length.

Table A4—Data for Figure 3 (Ti-5Al-5Zr-5Sn).

Test temp. (°F)	Prestress (psi)	Test life (s)	Method of heating	Orientation*
1200	70 000	63	resistant	
"	"	27	resistant	
"	"	60	resistant	T
"	65 000	117	resistant	
"	"	135	resistant	
"	"	160	radiant	
"	60 000	252	resistant	
"	"	242	resistant	
"	"	240	radiant	
"	"	160	radiant	T
"	55 000	344	resistant	
"	"	352	radiant	
"	"	300	radiant	T
"	50 000	1452	resistant	
"	"	684	resistant	
"	"	1243	resistant	T
"	"	1020	radiant	
1400	50 000	21	resistant	
"	"	15	resistant	
"	"	26	resistant	T
"	40 000	97	resistant	
"	"	157	resistant	
"	"	152	resistant	T
"	"	114	radiant	
"	"	91	radiant	T
"	35 000	257	resistant	
"	"	235	radiant	
"	"	202	radiant	T
"	30 000	679	resistant	
"	"	505	resistant	
"	"	382	resistant	T
"	"	600	radiant	
"	"	320	radiant	T
"	25 000	1819	resistant	
"	"	919	resistant	
"	"	1090	resistant	T
"	"	960	radiant	

Table A4 (concluded)

Test temp. (°F)	Prestress (psi)	Test life (s)	Method of heating	Orientation*
1600	30 000	10	resistant	
"	"	12	resistant	
"	"	26	resistant	T
"	"	12	resistant	T
"	"	11	resistant	T
"	20 000	85	resistant	
"	"	75	resistant	
"	"	50	resistant	T
"	"	60	resistant	T
"	"	45	radiant	T
"	"	50	radiant	
"	15 000	148	resistant	
"	"	310	resistant	
"	"	130	resistant	
"	"	212	resistant	T
"	"	233	resistant	T
"	"	180	radiant	T
"	10 000	309	resistant	
"	"	896	resistant	
"	"	1350	resistant	
"	"	1496	resistant	T
"	"	285	radiant	
1000	80 000	5	resistant	
"	"	5	resistant	
"	79 000	10	resistant	
"	77 000	1410	resistant	
"	"	1236	resistant	
"	75 000	3710	resistant	
"	"	3920	resistant	
"	"	3580	resistant	
"	"	2993	resistant	

*T—Specimens were taken transverse to the rolling direction. All other specimens were taken longitudinal to the rolling direction.

Note: The temperatures were held within +6 to 0 F° of the listed values over a 1.5-in. length.

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